EE5703 Industrial Drives Project

Industrial Robot Position Control

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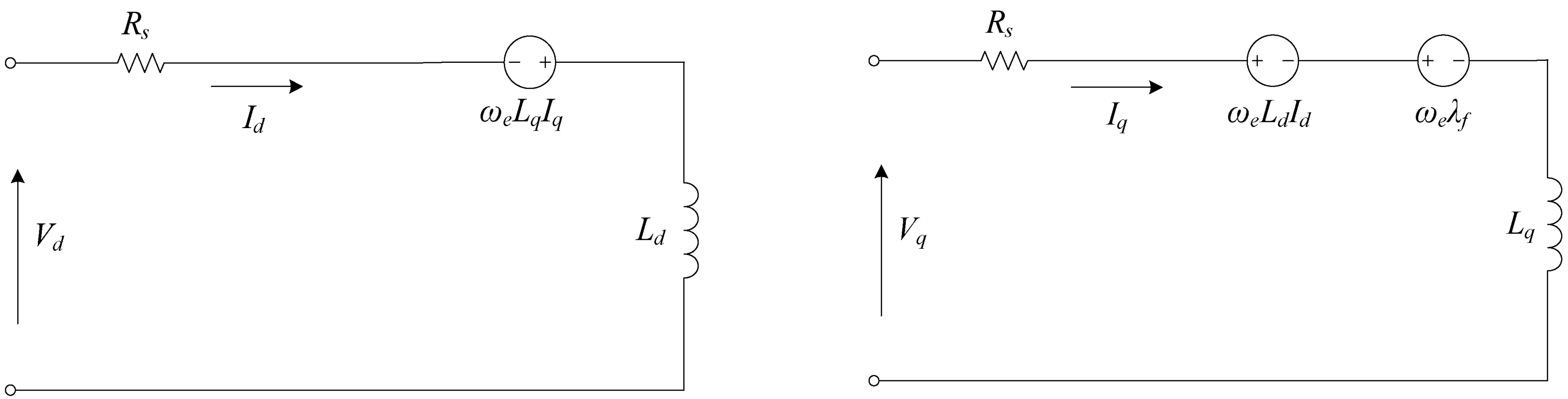
Mathematic model

We apply d-q axis coordinate model

The rotor lacks electromagnetic dynamics since the flux is generated by permanent magnets.



(a) (b)

Equivalent circuit

$$\vec{v}_{sd} = \vec{i}_{sd} r_s - w_s \psi_{sq} + \frac{d\psi_{sd}}{d\tau}$$

$$\vec{v}_{sd} = \vec{i}_{sd} r_s - w_s l_q i_{sq} + l_d \frac{di_{sd}}{d\tau}$$

$$\vec{v}_{sq} = \vec{i}_{sq} r_s + w_s \psi_{sd} + \frac{d\psi_{sq}}{d\tau}$$

$$\vec{v}_{sq} = \vec{i}_{sq} r_s + w_s l_q i_{sq} + w_s \psi_{r,m} + l_q \frac{di_{sq}}{d\tau}$$

Mathematatic model

$$\frac{di_{sd}}{d\tau} = -\frac{r_s}{l_d} i_{sd} + w_s \frac{l_q}{l_d} i_{sq} + \frac{v_{sd}}{l_d}$$

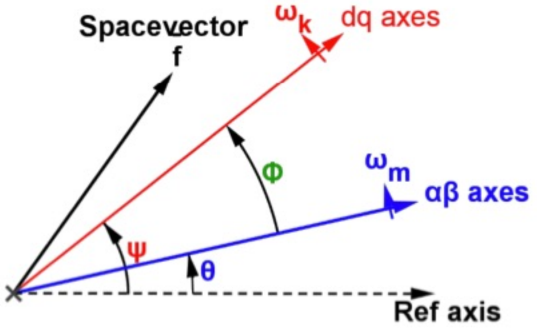
$$\frac{di_{sq}}{d\tau} = -\frac{r_s}{l_q} i_{sq} - w_s \frac{l_d}{l_q} i_{sd} - w_s \frac{\psi_{r,m}}{l_q} + \frac{v_{sq}}{l_q}$$

$$m_e = \vec{\psi_s} \times \vec{i_s} = \mathrm{Im}[\vec{\psi_s}^* \vec{i_s}]$$

$$= \psi_{r,m} i_{sq} + (l_d - l_q) i_{sd} i_{sq}$$

$$w_s = pw$$

$$\frac{dw}{d\tau} = \frac{m_e - m_L}{\tau_m}$$



$$\vec{v}_s = r_s \vec{i}_s + l_s \frac{d\vec{i}_s}{d\tau} + \frac{d\vec{\psi}_{r,m}}{d\tau}$$

$$\vec{\psi}_{r,m} = |\psi_{r,m}| e^{j\delta} = \psi_{r,m\alpha} + j\psi_{r,m\beta}$$

$$\vec{v}_s = r_s \vec{i}_s + l_s \frac{d\vec{i}_s}{d\tau} + j\omega_s \vec{\psi}_{r,m}$$

$$v_{s\alpha} = r_s i_{s\alpha} + l_s \frac{di_{s\alpha}}{d\tau} - \omega_s \psi_{r,m\beta}$$

$$v_{s\beta} = r_s i_{s\beta} + l_s \frac{di_{s\beta}}{d\tau} + \omega_s \psi_{r,m\alpha}$$

$$\frac{di_{sa}}{d\tau} = -\frac{r_s}{l_s} i_{sa} + \frac{v_{sa}}{l_s} - \frac{d\psi_a}{l_s dt}$$

$$\frac{di_{sb}}{d\tau} = -\frac{r_s}{l_s} i_{sb} + \frac{v_{sb}}{l_s} - \frac{d\psi_b}{l_s dt}$$

- d-q coordinate dynamic model is a commonly adopted and relatively straightforward.
- In our efforts to gain a deeper understanding of the PMSM and help us study we tried to model in stator coordinates.
- We can transform the equation on the d-q axis coordinate system to the α−β axis coordinate system using the rotation velocity relationship.
- Therefore, the voltage equation in the α − β coordinate system can be expressed as

PMSM Steady State Model

In real practice, the motor almost work in steady state.

Hence, we need to keep torque output constant.

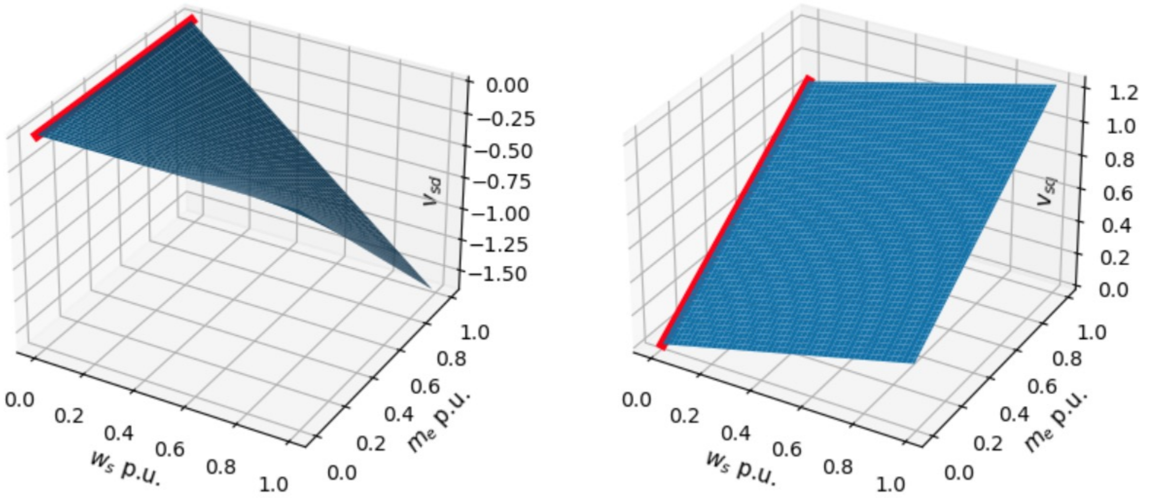
For steady state, $\dfrac{di_{sd}}{d\tau} = 0\,,\ \dfrac{di_{sq}}{d\tau} = 0\,,\ \dfrac{dw}{d\tau} = 0$

$$\vec{v}_{sd} = \vec{i}_{sd} r_s - w_s \psi_{sd}$$

$$\vec{v}_{sd} = \vec{i}_{sd} r_s - w_s l_q i_{sq}$$

$$\vec{v}_{sq} = \vec{i}_{sq} r_s + w_s \psi_{sd}$$

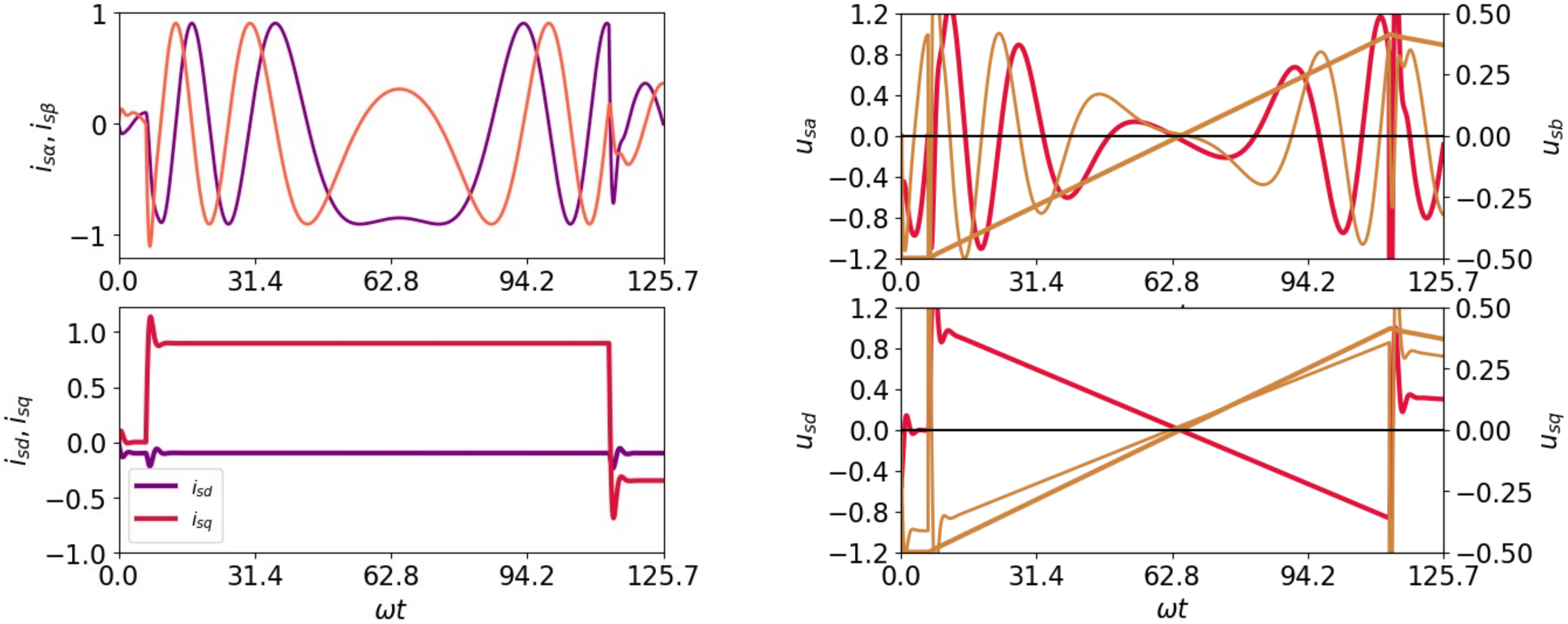
$$\vec{v}_{sq} = \vec{i}_{sq} r_s + w_s l_d i_{sd} + w_s \psi_{r,m}$$



- Respective variation of $\vec{v}_{sd}$ and $\vec{v}_{sq}$ to w_s and m_e
- Servo steady state ($w_s = 0$) is indicated by red line

Dynamic simulation

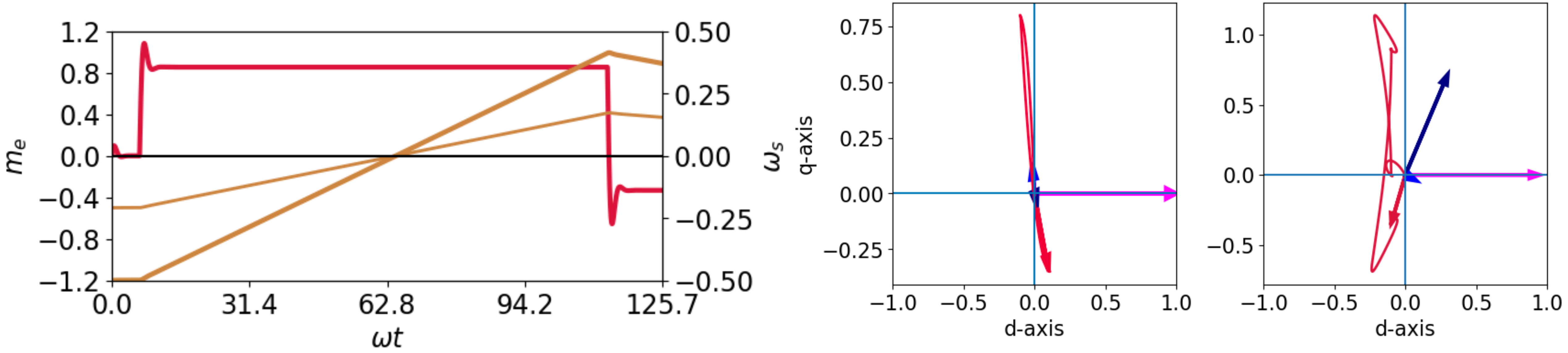
Initial rotational velocity of -5 rad/s. Current i_q to 0.8 then to -0.35.



$r_s = 0.1729$,
$l_q = 0.6986$,
$l_d = 0.4347$,
$\tau_m = 50.5$

- For both models we can see the the rotational speed initiates from -0.5 and progressively accelerates, reversing direction.
- It also proves that the d-q coordinates method is much more straightforward for accomplishing precise current control compared with Stator coordinate model.

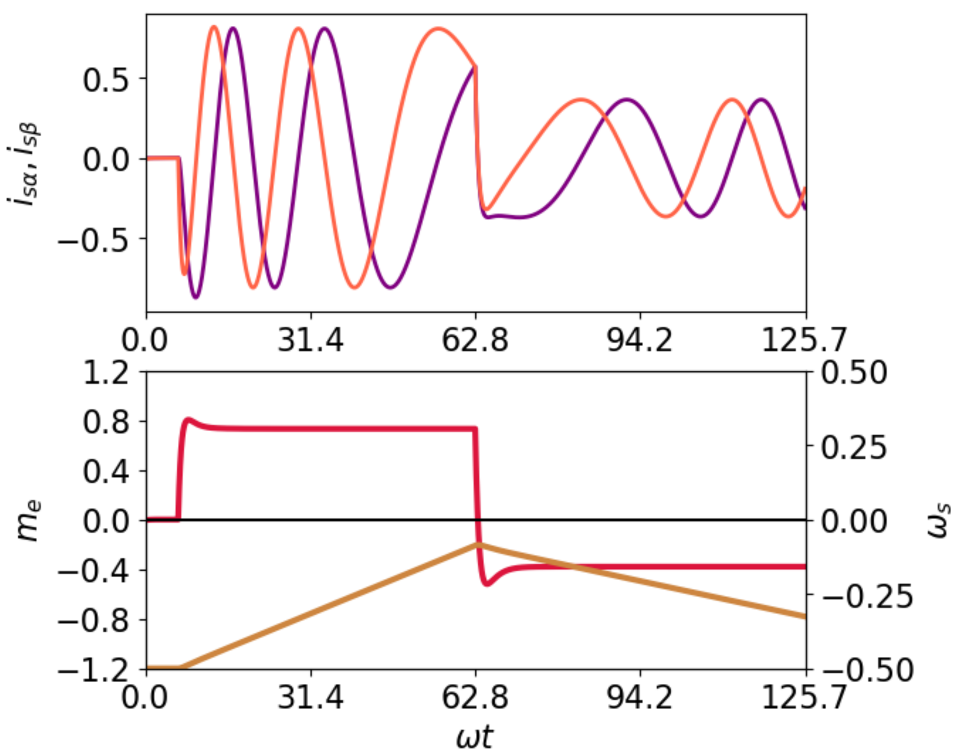
Dynamic simulation



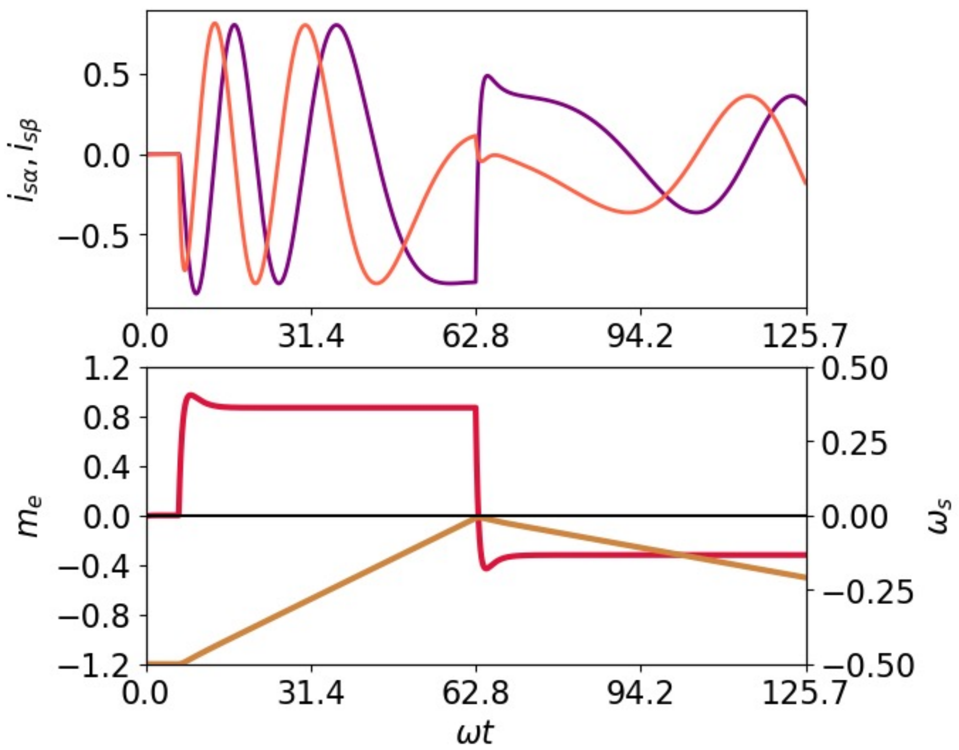
- Even though there is a smooth and slightly overshooting current initiation, the output torque and rotational speed exhibit seamless transitions without significant overshooting or oscillations.
- For current trajectory the q-axis current undergoes significant changes, underscoring its primary role in torque control.
- It demonstrates the q-axis current is the main contributor to torque regulation.

Dynamic simulation

$l_d < l_q$



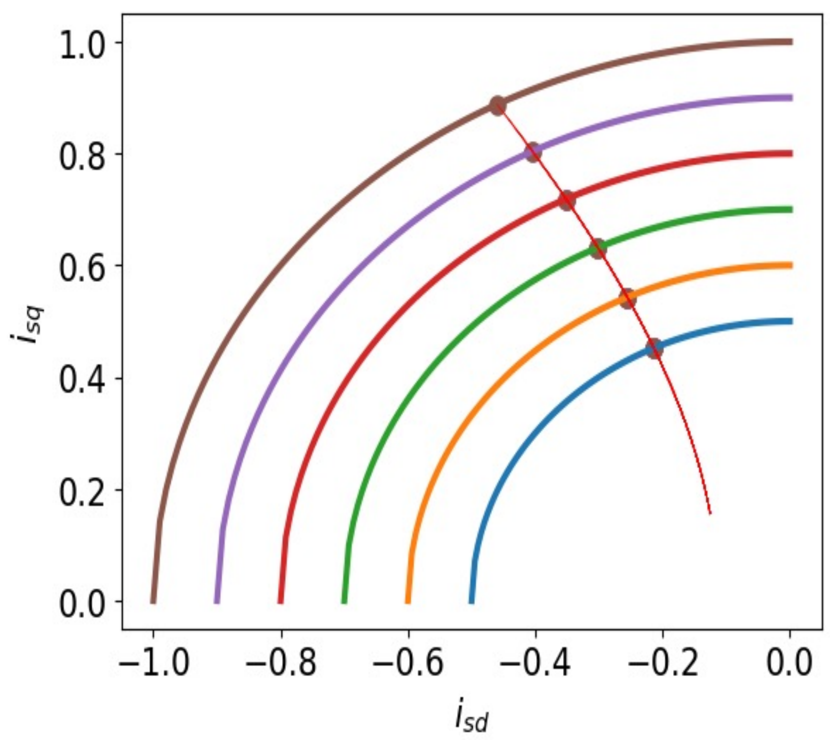
$l_d > l_q$



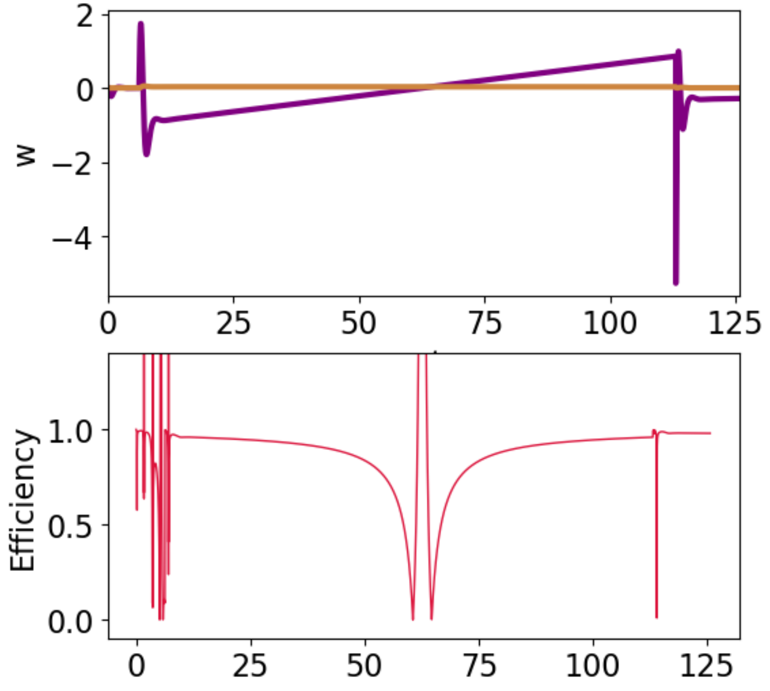
- For the other two situations, demonstrate effective control of current and rotation speed.
- The primary distinction lies in the rotational acceleration. when $l_d > l_q$, the acceleration is notably higher compared to the scenario with $l_d < l_q$.
- A larger l_d results in a more robust field along the d-axis, augmenting the motor's torque production capacity.

Mathematic model

Maximum Torque per Ampere(MPTA)



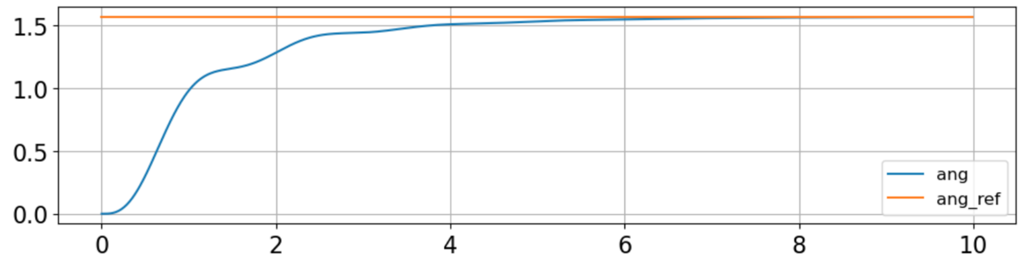
Power and efficiency



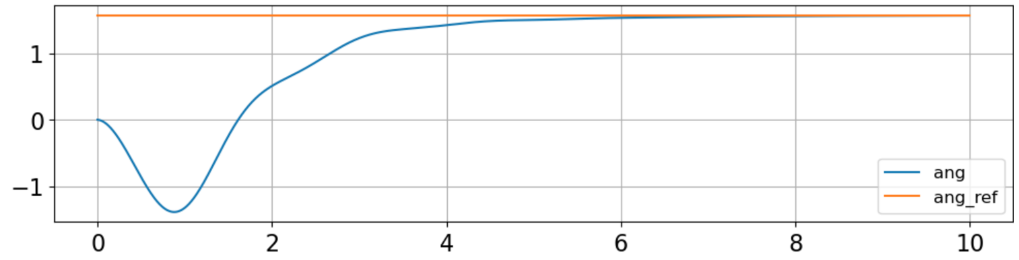
- The simulation reveals that the MPTA position is not linearly related to i_d and i_q.
- So it's crucial to find the MPTA point in reality to improve the overall efficiency of robot operations.

- The efficiency remains consistently high, nearing 1 in most conditions.
- However, fluctuations are observed when the current or rotor changes direction.

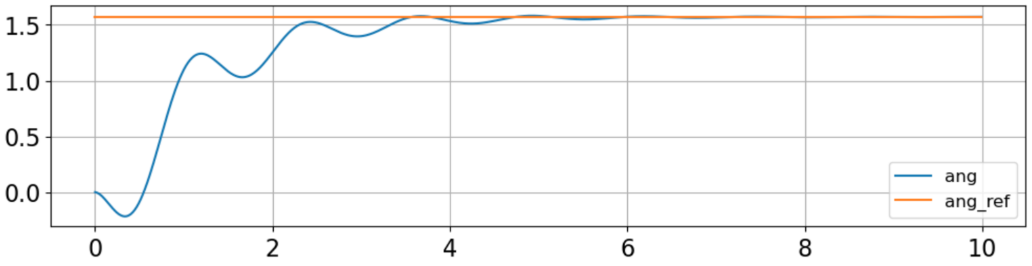
Cascade PID Control



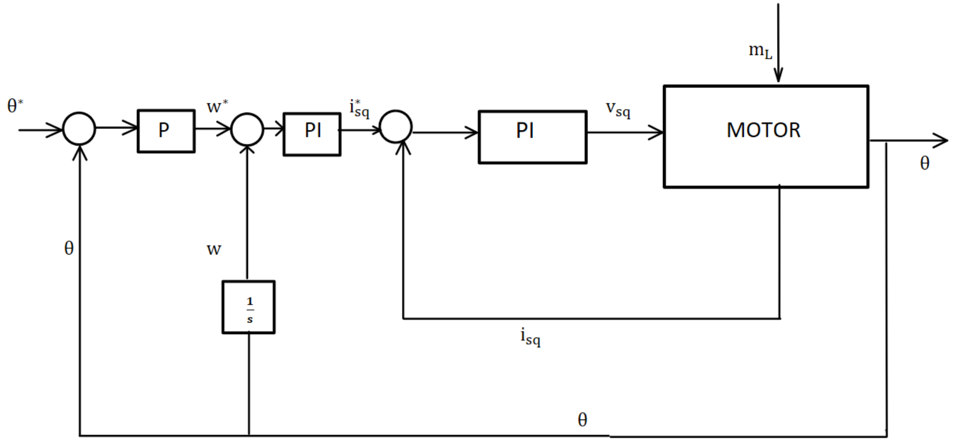
Position step response: ∠90°, no load



Position step response: ∠90°, m_L = 0.15 p.u.



Position step response: ∠90°, m_L = 0.15 p.u., extended voltage limit



Angular position-velocity cascade control

$r_s = 0.3264$, $l_q = 1.459$, $l_d = 3.622$, $\tau_m = 4.488$

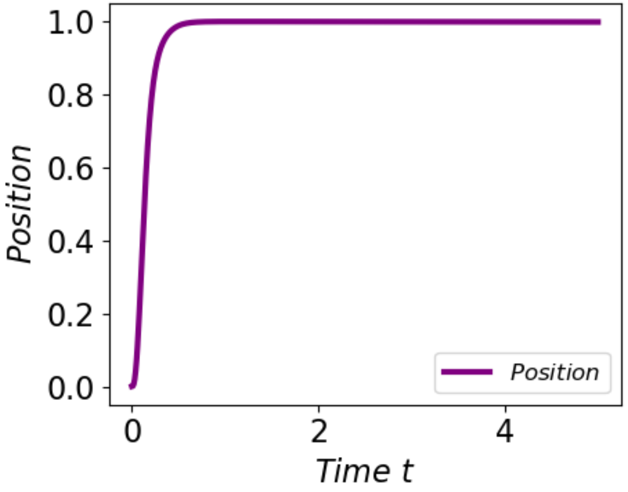
- No overshoot, but long settling time;
- Slow recovery from load torque;
- Less undershoot caused by load if voltage limit is extended to 5 p.u.;

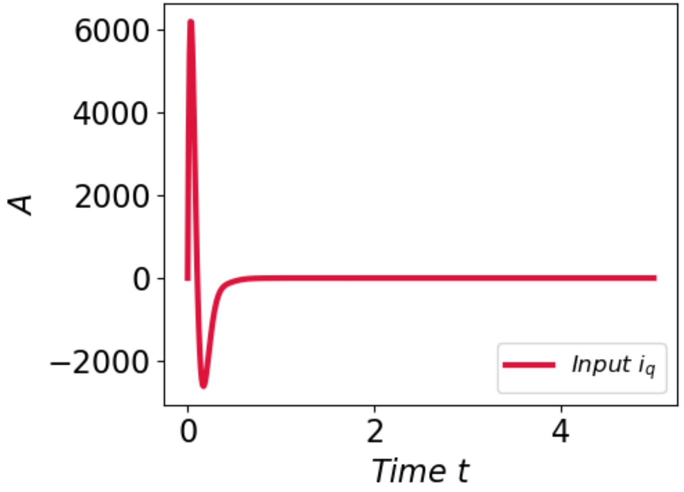
Augmented matrix LQR

$r_s = 0.1729,$
$l_q = 0.6986,$
$l_d = 0.4347,$
$\tau_m = 50.5$

In order to get better performance of controller we applied augmented matrix control

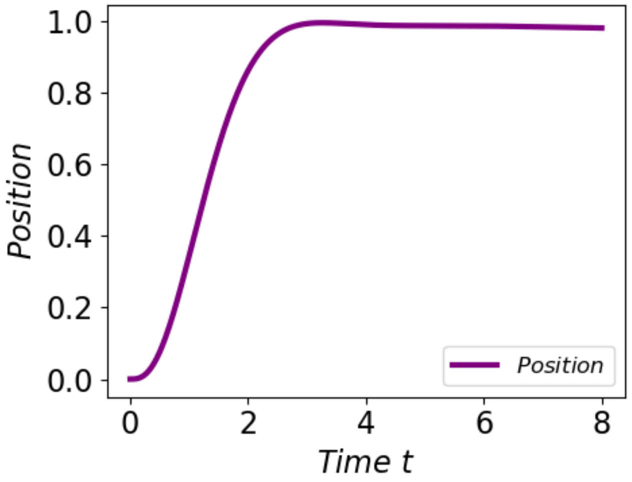
The control result is ideal, fast response and precise position.

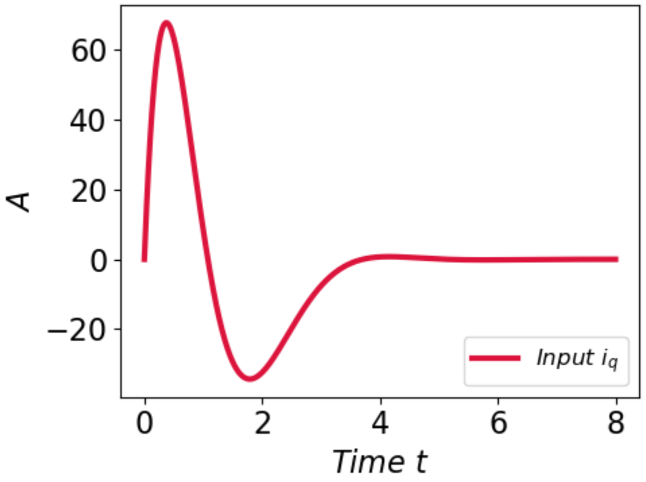




The control input signal requirement is too high to meet in reality.

Change to another pair of Q and R, the result is still good.



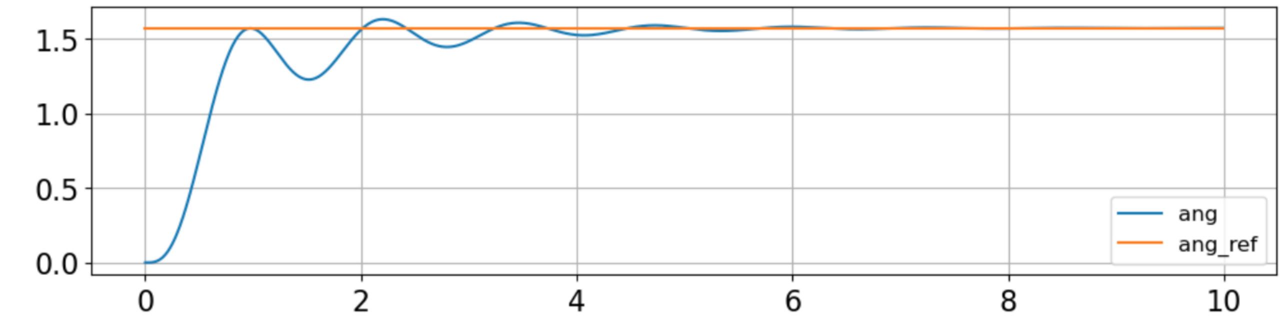


The input signal is reachable.

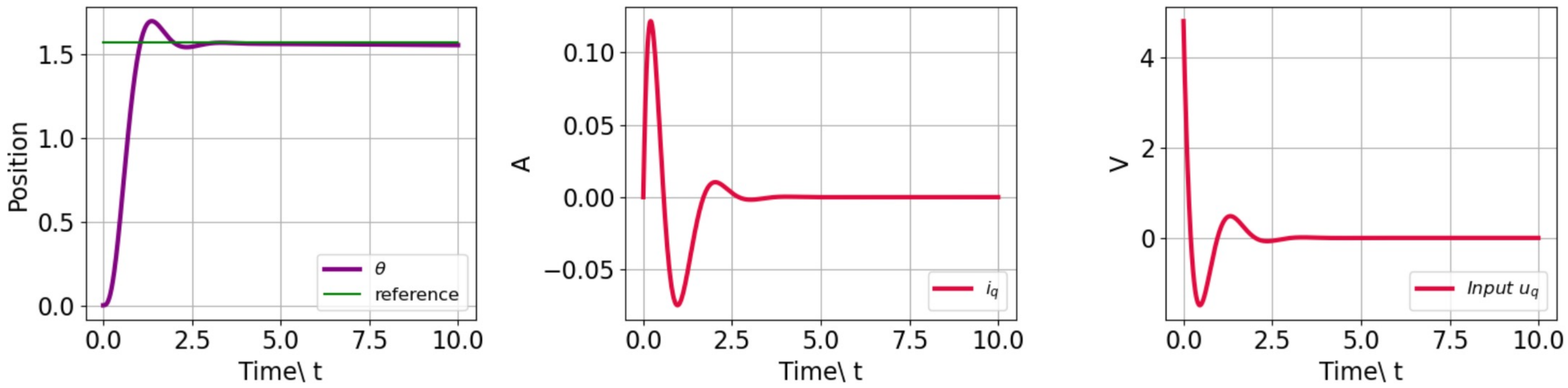
Comparation

$$r_s = 0.3264,\ l_q = 1.459,\ l_d = 3.622,\ \tau_m = 4.488$$

PID



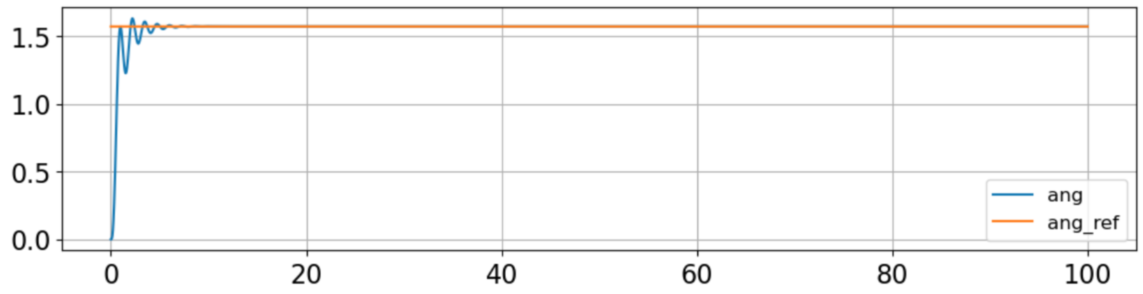
LQR



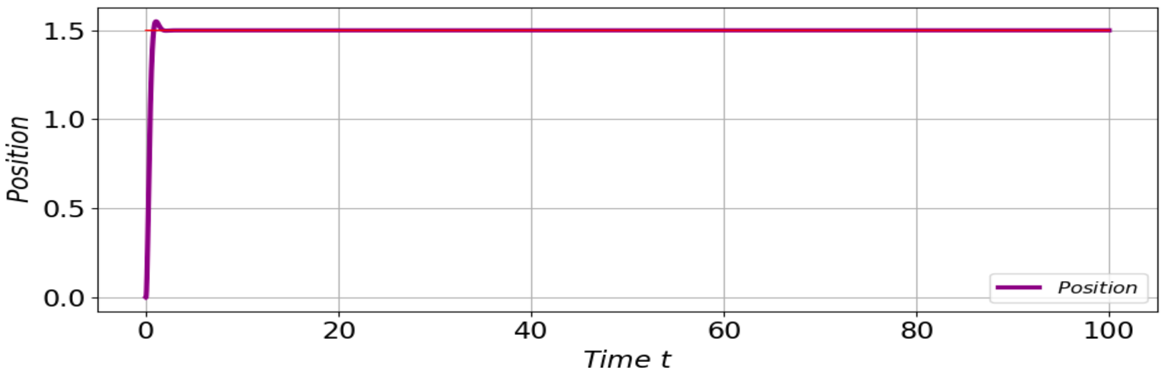
- Carefully tuned Q and R helps to overcome the problem of LQR control signal;
- LQR performs much better than PID.

Comparation

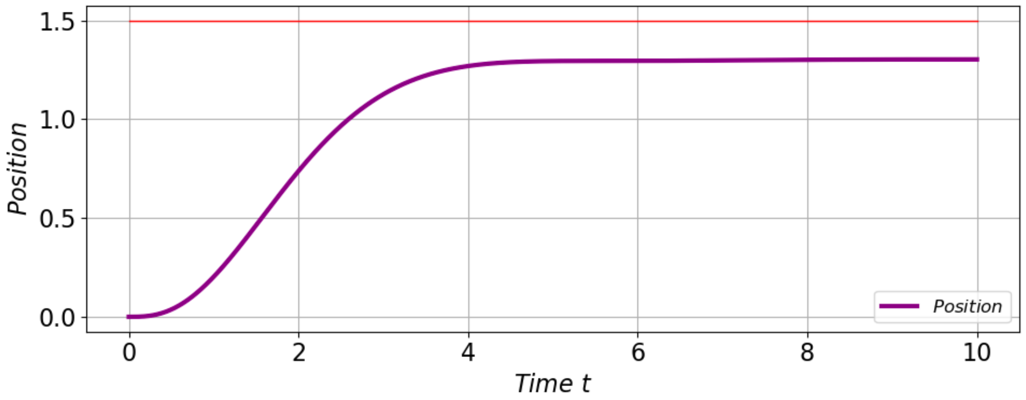
PID



LQR



LQR, disturbance



- For long time simulation two methods Still work well

- For LQR part, we try to build a disturbance reject system but not work well this can be the future research direction for us.

Conclusion

- This project evaluates a PMSM for industrial robot position control, covering dynamic equations, steady-state analysis, and key motor characteristics.

- The report compares position control using PID and LQR methods.

- In the end we compared two position control PID and LQR and get the conclusion that LQR is a better choice for precise position control despite some unsolved defects.

- Most importantly, these practice enhances our theoretical understanding learnt in class.